



## Particle acceleration and the origin of gamma-ray emission from Fermi Bubbles. (Expanded version of the talk at the 32nd ICRC)

D.O. CHERNYSHOV<sup>1,2,3</sup>, K.-S. CHENG<sup>2</sup>, V.A. DOGIEL<sup>1</sup>, C.M. KO<sup>2,3</sup>, W.-H. IP<sup>3</sup> AND Y. WANG<sup>2</sup>

<sup>1</sup>*I.E.Tamm Theoretical Physics Division of P.N. Lebedev Institute of Physics, Leninskii pr. 53, 119991, Moscow, Russia*

<sup>2</sup>*Department of Physics, The University of Hong Kong, Pokfulam Road, Hong Kong, China*

<sup>3</sup>*Institute of Astronomy, National Central University, Zhongli 320, Taiwan*

chernyshov@td.lpi.ru

**Abstract:** Fermi LAT has discovered two extended gamma-ray bubbles above and below the galactic plane. We propose that their origin is due to the energy release in the Galactic center (GC) as a result of quasi-periodic star accretion onto the central black hole. Shocks generated by these processes propagate into the Galactic halo and accelerate particles there. We show that electrons accelerated up to  $\sim 10$  TeV may be responsible for the observed gamma-ray emission of the bubbles as a result of inverse Compton (IC) scattering on the relic photons. We also suggest that the Bubble could generate the flux of CR protons at energies  $> 10^{15}$  eV because the shocks in the Bubble have much larger length scales and longer lifetimes in comparison with those in SNRs. This may explain the the CR spectrum above the knee.

**Keywords:** Galaxy: halo – radiation mechanisms: non-thermal — acceleration of particles — shock waves

## 1 Introduction

Fermi bubbles are symmetric structures elongated above and below the Galactic plane for about 8 kpc [16]. Their discovery is one of the most remarkable events in astrophysics. The origin of the bubble is still enigmatic and up to now a few models were presented in the literature. The team, which subtracted this structured gamma-ray emission from the total diffuse galactic emission presented different explanations of the phenomenon though they seem to trend towards the model of a single huge energy release in the Galactic center (GC) when about 10 million years ago a huge cloud of gas or a star cluster was captured by the central black hole that produced the Fermi bubbles seen today. Gamma-rays in their model are produced by the inverse Compton scattering of the electrons on relic photons. In [15] it was assumed that these electrons were accelerated in the bubble interior by a hypothetical MHD turbulence excited behind the termination shock generated at the edges of the bubbles. Another interpretation was presented by [10] who proposed a relatively slow energy release ( $\sim 10^{39}$  erg s<sup>-1</sup>) due to supernova explosions as a source of proton production in the GC which emitted gamma-rays there.

An alternative explanation based on the assumption that the energy for the Fermi bubbles was originated from star capture events which occurred in the GC every  $10^4 - 10^5$  years was suggested by [9]. About one thousands of such events form giant shocks propagating through the central part of

the Galactic halo and thus produce accelerated particle responsible for the bubble emission.

Processes of particle acceleration by the bubble shocks in terms of sizes of the envelope, maximum energy of accelerated particles, etc. may differ significantly from those obtained for SNs that may lead to the maximum energy of accelerated particles much larger than can be reached in SNRs. In this respect, we assume that acceleration of protons in Fermi bubbles may contribute to the total flux of the Galactic cosmic rays (CR) above the “knee” break ( $\geq 10^{15}$  eV).

## 2 Structure of Shocks in the Fermi Bubble

As it was assumed in [9] the central massive black hole captures a star every  $\tau_0 \sim 10^4 - 10^5$  years and as a result releases energy about  $\mathcal{E}_0 \sim 10^{52}$  erg in the form of subrelativistic particles which heat the central  $\leq 100$  pc in the GC. This heating produces a shock propagating into the surrounding medium [18]. For an exponential atmosphere with the plasma density profile

$$\rho(z) = \rho_0 \exp\left(-\frac{z}{z_0}\right), \quad (1)$$

an analytical solution for permanent energy injection by star accretion was obtained by [13]. Here  $z$  is the coordinate perpendicular to the Galactic plane. The radius of

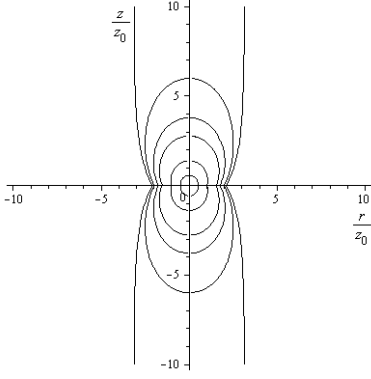


Figure 1: The bubble multi-shock structure.

the bubble as a function of the height  $z$  and the time  $t$  is

$$r = 2z_0 \arccos \left[ \frac{1}{2} e^{\frac{z}{2z_0}} \left( 1 - \left( \frac{y}{2z_0} \right)^2 + e^{-\frac{z}{z_0}} \right) \right], \quad (2)$$

where

$$y = \int_0^t \left( \frac{\gamma_g^2 - 1}{2} \lambda \frac{\alpha W t}{V(t) \rho_0} \right)^{0.5} dt, \quad (3)$$

$V$  is a current volume enveloped by the shock

$$V(t) = 2\pi \int_0^{a(t)} r^2(z, t) dz, \quad (4)$$

$a$  is the position of the shock top

$$a(t) = -2z_0 \ln \left( 1 - \frac{y}{2z_0} \right), \quad (5)$$

$W = \mathcal{E}_0/\tau_0$  is the average luminosity of the central source,  $\gamma_g$  is the polytropic coefficient, and  $\alpha$  and  $\lambda$  are numbers [7].

Depending on capture parameters one can imagine the bubble interior as a volume filled with many shocks of different ages (see Fig.1).

### 3 Particle Acceleration by the Bubble Shocks

Correct analysis of shock acceleration in the bubble requires sophisticated calculations of each stage of this process which we hope to perform later. Now we present simple estimates of characteristics of accelerated spectra. We analyze spectra of protons and electrons separately because they are formed by completely different processes and as we later conclude their spectral characteristics differ strongly from each other. We present also the spectrum of gamma-ray emission produced by the inverse Compton (IC) scattering of the accelerated electrons in the bubble.

#### 3.1 Proton Spectrum

Below we analyse the spectrum of protons accelerated in the bubble and discuss whether the bubble contribution to the total flux of CRs in the Galaxy may explain the knee steepening. We remind that the generally accepted point of view is that the flux of relatively low energy CRs ( $< 10^{15}$  eV) is generated by SNRs which ejects a power-law spectrum  $E^{-2}$  into the interstellar medium. This spectrum is steepened by propagation (escape) processes in the Galaxy in accordance with the spectrum observed near Earth (for details see [6]). However these sources can hardly produce CRs with energies more than  $10^{15}$  eV (see [4, 5]). Just at this energy a steepening (the knee) in the CR spectrum is observed. We assume that the bubble may generate the flux of CRs at energies above  $10^{15}$  eV. The origin of CRs with energies above  $10^{15}$  eV is the goal of this subsection. It is natural to assume that the bubble shocks may produce this flux considering their large scales and long lifetimes.

In the framework of our model one can imagine the bubble as at cylinder of the radius  $\sim 3 - 6$  kpc filled with hundreds of shocks propagating in series one after another (see Fig. 1). The frequency of shock injection (star capture) is poorly known parameter, especially for the conditions of the GC. From the analysis of shock hydrodynamics we estimated the age of outer shock by  $10^8$  yr though this value depends strongly on parameters of the self-similar solution which is an idealization of conditions in the Galaxy. The frequency of star capture by a central black hole is estimated from theoretical treatments  $\nu \sim 10^{-4} - 10^{-5} \text{ yr}^{-1}$  [2]. Thus, a multi-shock structure can be produced by the capture processes with an average distance  $L$  between separate shocks given by

$$L = \tau_{cap} u = 30(\nu \times 3 \times 10^4 \text{ yr})(u/10^8 \text{ cm/s}) \text{ pc}. \quad (6)$$

On the other hand there is another spatial scale which characterizes processes of particle acceleration by a single shock which is  $l_D \sim D/u$  where  $D$  is the spatial diffusion coefficient near a shock and  $u$  is the shock velocity. Depending on the relation between  $L$  and  $l_D$  there may be different regimes of acceleration in the bubble. This problem of particle acceleration in supersonic turbulence or multi-shock structure was analyzed in [8]. The acceleration regime is characterized by a dimensionless parameter

$$\psi = \frac{L}{l_D} = \frac{uL}{D}, \quad (7)$$

If  $\psi \ll 1$ , the diffusion length scale of a single shock  $l_D$  exceeds the distance between shocks  $L$ . Therefore, particle are accelerated by interactions with many shocks that gives the acceleration similar to the classical stochastic Fermi acceleration. The critical energy  $E_1$  for this regime of acceleration is estimated from the condition  $\psi \sim 1$  or  $l(E_1) \sim L$ . In the Bohm limit with the diffusion coefficient  $D \sim cr_L(E)/3$  where  $r_L(E) = E/eB$  is the particle

Larmor, the value of  $E_1$  is

$$E_1 \sim \frac{eBLu}{c} = 10^{15} \left( \frac{B}{5\mu G} \right) \left( \frac{L}{30pc} \right) \left( \frac{u}{10^8 cm/s} \right) \text{ eV.} \quad (8)$$

which is about the position of the knee break.

The kinetic equation for the case  $\psi \ll 1$  ( $E \gg E_1$ ) only contains the diffusion in the spatial and momentum spaces (Fermi stochastic acceleration) and has the form

$$\frac{\partial}{\partial z} \left( D(\rho, p) \frac{\partial f}{\partial z} \right) + \frac{1}{\rho} \frac{\partial}{\partial \rho} \left( D(\rho, p) \rho \frac{\partial f}{\partial \rho} \right) + \frac{1}{p^2} \frac{\partial}{\partial p} \left( \kappa(\rho, p) p^2 \frac{\partial f}{\partial p} \right) = -Q(\rho, z, p), \quad (9)$$

where  $\rho$  and  $z$  are the cylindrical spatial coordinates,  $p$  is the particle momentum.  $D(\rho, p)$  is the spatial diffusion coefficient and  $\kappa(\rho, p)$  is the momentum diffusion coefficient,

$$\kappa \sim \frac{u^2}{cL} p^2. \quad (10)$$

The term  $Q(\rho, z, p)$  describes CR injection by supernova remnants in the disk with energies  $E < 10^{15}$  eV and with observed power-law spectrum.

The momentum dependence of  $f$  can be presented by a power-law function,  $f(p) \propto p^{-\gamma}$ , where  $\gamma$  should be determined from Eq.(9):

$$\gamma \simeq \frac{3}{2} + \sqrt{\frac{9}{4} + \frac{cLD_0}{u^2 H^2}} \quad (11)$$

where  $H$  is the height of the Galactic halo and  $D = D_0(E/E_0)^\xi$  is the average diffusion coefficient in the Galaxy. For  $H \simeq 10$  kpc,  $D_0 \simeq 3 \times 10^{29} \text{ cm}^2 \text{ s}^{-1}$ ,  $\xi \simeq 0.3$ ,  $E_0 \simeq 3$  GeV [17] and  $u = 10^8$  cm/s,  $L = 30$  pc we have  $\gamma \simeq 5$ , i.e., the power-law spectrum above  $10^{15}$  eV is in the form  $N(E) \propto E^{-3}$  as necessary for the knee spectrum. The proton spectrum derived from Eq. (9) is shown in Fig. 2.

### 3.2 Electron Spectrum and Spatial Distribution

Unlike protons relativistic electrons lose their energy effectively by synchrotron and inverse Compton radiation. The rate of energy loss of electrons is

$$\frac{dE}{dt} = -\beta E^2 = -c\sigma_T (w_H + w_{ph}) \left( \frac{E}{m_e c} \right)^2. \quad (12)$$

The maximum energy of electrons  $E_{max}$  can be estimated if the spatial diffusion coefficient at the shock  $D_{sh}$  is known. From Eq. (12) we have

$$E_{max}^e \sim \frac{u^2 c}{\beta D_{sh}} \quad (13)$$

For the Bohm diffusion coefficient we can estimate the upper limit for  $E_{max}^e$  which is

$$E_{Bmax}^e \sim \sqrt{\frac{eHu^2}{3c\beta}}. \quad (14)$$

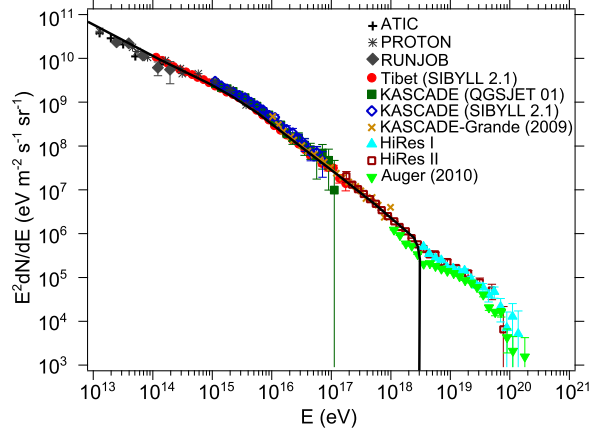


Figure 2: The Bubble contribution to the flux of CRs. Tibet, KASCADE, HiRes and Auger data are summarized in [14]. ATIC data are from [1], Proton data are from [12], RUNJOB data are from [3].

that gives for the velocity  $u = 10^8 \text{ cm s}^{-1}$ , the magnetic field strength  $H = 10^{-5} \text{ G}$  and  $w_{ph} = 0.25 \text{ eV cm}^{-3}$  the maximum energy of accelerated electrons about  $E_{Bmax} \sim 5 \times 10^{13} \text{ eV}$ , i.e., for electrons  $E < E_{Bmax} \ll E_1$ . It follows from this inequality that electrons are accelerated in the regime  $\psi \gg 1$  (single shock acceleration). Kinetic equations for this case were derived in [8].

In the case of electrons there is one more spatial parameter essential for acceleration by shocks, namely the electron mean free path  $\lambda$ . Therefore we have two more dimensionless parameters which describe electron acceleration in the case of supersonic turbulence,  $l_{sh}/\lambda$  and  $l_D/\lambda$ . Nearby shocks electrons propagate by diffusion, and  $\lambda$  there is a function of energy

$$\lambda_D(E) \sim \sqrt{\frac{D}{\beta E}} \quad (15)$$

From Eq. (13) one can see that for  $E < E_{max}^e$  we have  $\lambda > l_D$ , i.e., acceleration by shocks is effective.

Far away from shocks electrons propagate by convection and for the velocity  $u$  the mean free path is

$$\lambda_V(E) \sim \frac{u}{\beta E} \quad (16)$$

For relatively low energy electrons  $\lambda(E) > l_{sh}$ , and a regime of multi-shock acceleration for electrons is realized in this case where interactions with many shocks change slowly the shock to  $E^{-1}$  (for details see [8]) which produces a hard  $E^{-1}$  spectrum. The break position  $E^*$  between the single shock and multi-shock spectra follows from the equality  $\lambda(E^*) = l_{sh}$

$$E^* \sim \frac{u}{\beta l_{sh}} \quad (17)$$

that gives, e.g.,  $E^* \sim 2.8 \times 10^{11} \text{ eV}$  for  $l_{sh} = 10^{21} \text{ cm}$ .

If we assume that the bubble gamma-rays are produced by IC scattering of electrons on the relic photons, then it follows from our model that: 1. a drop of the bubble gamma-ray flux at  $E_\gamma < 1$  GeV as observed by [16] is due to a flattening of electron spectrum at  $E < E^*$ ; and 2. a drop of this spectrum in the range  $E_\gamma > 100$  GeV is due to a cut-off in the electron spectrum at  $E \sim E_{max}^e$ . The expected spectrum of gamma-ray emission from the Bubble due to IC scattering of the electrons is shown in Fig. 3.

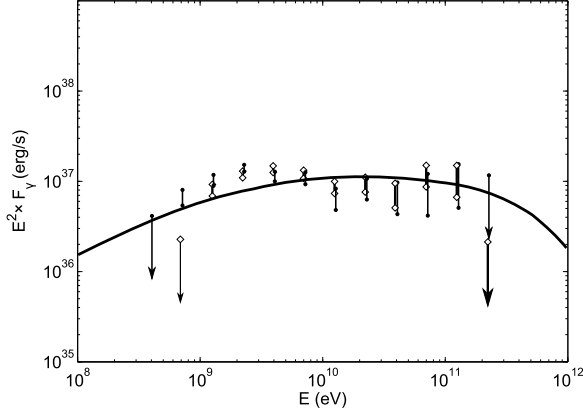


Figure 3: The spectrum of gamma-ray emission from Fermi bubble in case of multi-shock acceleration. Data points are taken from [16].

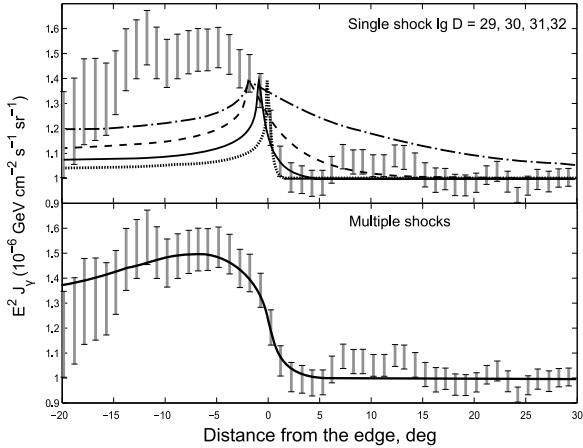


Figure 4: Spatial distribution of the gamma-ray emission. Data are from [16]. *Top*: in case of single shock. Dotted line correspond to  $D=10^{29}$  cm<sup>2</sup>/s, solid to  $D=10^{30}$  cm<sup>2</sup>/s, dashed to  $D=10^{31}$  cm<sup>2</sup>/s and dash-dotted  $D=10^{32}$  cm<sup>2</sup>/s, *Bottom*: in case of several shocks distributed in accordance with (2).

In Fig. 4 we show an expected spatial distributions of gamma-ray emission from the bubble for the single shock and multiple shocks cases. For the multiple shocks it was assumed that they distributed in accordance to the solution (2) and it was also assumed that the amount of accelerated electrons is proportional to the density of shocks. From this figure one can see that the single shock model (without the second order Fermi acceleration in the bubble interior) is

unable to reproduce the data. However, for the parameters of star capture model these data are nicely described.

## 4 Conclusion

We have shown that series of shocks produced by a sequential stellar captures by the central black hole can further re-accelerate the protons emitted by SNRs up to energies above  $10^{15}$  eV. The predicted CR spectrum contributed by the Bubble may be  $E^{-\nu}$  where  $\nu \sim 3$  for  $10^{15}$  eV  $< E < 10^{19}$  eV that explains the knee CR spectrum.

The regime of electron acceleration in the bubble is quite different from that of protons. It is a combination of single and multishock accelerations. In this case we have a cut-off of the electron spectrum at  $E > 3 \cdot 10^{13}$  eV and flattening of the spectrum at  $E < 100$  GeV that explains nicely the bubble gamma-ray spectrum and the sharp edge spatial distribution observed by [16] if this emission is due to IC on the relic photons

## Acknowledgements

DOC and VAD are partly supported by the NSC-RFBR Joint Research Project RP09N04 and 09-02-92000-HHC-a. KSC is supported by the GRF Grants of the Government of the Hong Kong SAR under HKU 7011/10P. CMK is supported, in part, by the Taiwan National Science Council Grant NSC 98-2923-M-008-01-MY3 and NSC 99-2112-M-008-015-MY3. WHI is supported by the Taiwan National Science Council Grant NSC 97-2112-M-008-011-MY3 and Taiwan Ministry of Education under the Aim for Top University Program National Central University.

## References

- [1] Ahn, H. S. et al., ICRC, 2008, 2, 79
- [2] Alexander, T., PhR, 2005, 419: 65
- [3] Apanasenko, A. V. et al., ICRC, 2001, 1622
- [4] Bell, A. R., MNRAS, 2004, 353: 550
- [5] Berezhko, E. G. & Voelk, H. J., A&A, 2000, 357: 283
- [6] Berezhinskii, V. S. et al, 1990, Astrophysics of Cosmic Rays, ed. V.L.Ginzburg, Norht-Holland, Amsterdam
- [7] Bisnovatyi-Kogan, G. S., Silich, S. A., RvMP, 1995, 67: 661
- [8] Bykov, A. M. & Toptygin, I. N., Physics Uspekhi, 1993, 36, 1020
- [9] Cheng, K.-S. et. al., ApJ, 2011, 731, L17
- [10] Crocker, R. M., Aharonian, F., PhRvL, 2011, 106: id.101102
- [11] Dogiel, V. et. al., PASJ, 2009, 61: 1099
- [12] Grigorov, N. L. et al., ICRC, 5, 1746
- [13] Kompaneets A. S., Akademiia Nauk SSSR, Doklady (DoSSR, in Russian), 1960, 130, 5
- [14] Kotera, K. & Olinto, A. V., 2011, astro-ph 1101.4256

- [15] Mertsch, P. & Sarkar, S., 2011, PRL, 107, 091101
- [16] Su, M., Slatyer, T. R., Finkbeiner, D. P., ApJ, 2010, 724: 1044
- [17] Strong, A. W., Moskalenko, I. V., ApJ, 1998, 509, 212
- [18] Weaver, R., McCray, R., Castor, J., Shapiro, P., Moore, R., ApJ, 1977, 218, 377